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ELECTROSTATIC SENSITIVITY TESTING FOR EXPLOSIVES

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by

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ABSTRACT

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The advantages and disadvantages of the present methods are discussed with the emphasis on the appropriateness of each method in determining a minimum energy for initiation. The properties of the electric discharge circuits, particularly the effects of the series resistances and storage capacitors on discharge rate that govern the energy delivery to the spark gap, are analyzed. To develop testing procedures that will yield a more meaningful characterization of the sensitivity of primary explosives, a testing methodology that involves the use of a sensitivity map, a type of response surface, is introduced. Important remaining questions in the field of electrostatic sensitivity testing are outlined; proposed is a research program that should lead to improved procedures and a better understanding of electrostatic spark initiation.

INTRODUCTION

Spark sensitivity testing can provide an important measure of the electrostatic hazards associated with the handling of primary explosives. The threshold (or minimum) energy required for initiation is of particular concern. The usual approach to determine this minimum energy is to discharge a capacitor through a spark gap in or near the explosive and to reduce the stored energy in the capacitor until no ignition occurs in a specified number of trials. Usually a new explosive sample is used for each trial. Despite the apparent simplicity of this technique, the large number of variables present in the test makes a quantitive interpretation of the results difficult. The electrical circuit, spark gap-explosive geometry, ambient conditions, and, of course, the nature of the explosive, all play important roles. Since all of these parameters simultaneously affect the test, their separate roles are not easily understood.

Two approaches have been taken in the past to determine the electrostatic sensitivity of primary explosives. One was to measure and to control the energy actually delivered to the spark gap; i.e., one can, in principle, control all of the variables and establish not only the minimum energy required for ignition but also the dependance of ignition probability on experimental variables. This approach has been followed by Moore, Sumner, and Wyatt (subsequently referred to as MSW) (Ref 1 - 6) and by Gentner (Ref 7). The other, more traditional approach was to abandon extensive analysis of the circuit, energy delivery, and to design a test apparatus that was capable of producing comparisons among explosives, and was safe and convenient. The rationale in this case was that it was considered feasible to determine the relative sensitivity or ranking of the explosive tested among other explosives despite the fact that an absolute minimum energy could not be measured. This standard approach has been followed in the designs of the tests at Picatinny Arsenal and at the Naval Ordnance Laboratory.

No attemps have been made to correlate the results of these two approaches; i.e., no one has shown that these relative sensitivity tests indeed properly rank or order the sensitivities of the explosives based upon absolute sensitivity tests. None of the standard tests at Picatinny or NOL has been sufficiently evaluated to determine the fraction of stored energy actually delivered to the spark gaps or to determine the delivery rate. The standard tests, may, in fact,

measure rather secondary properties of the spark gap and explosive. In addition, the standard tests to not attempt to measure the electrostatic sensitivity of primary explosives in their most sensitive configurations, e.g., contact discharge (discussed subsequently in Section 3). On the other hand, in the absolute sensitivity tests, explosives were studied only under special conditions: as dry-powder, controlled humidity, etc. It is not possible to predict from these results the hazards that one is likely to encounter in a laboratory or production line.

Consequently, there is an evident need to determine whether the standard sensitivity tests accurately reflect the true sensitivities of primary explosives; and whether a relative sensitivity test can indeed be used to establish the true sensitivities of primary explosives over a wide range of conditions. The purposes of this report are to review electrostatic sensitivity testing, to provide a critique of the spark initiation tests used at Picatinny and NOL, and to outline a research program with the objective to develop improved testing procedures and a better understanding of electrostatic sensitivity.

The organization of this memorandum is as follows: In Section 2, earlier studies of spark initiation are reviewed; emphasis is placed upon the work of MSW. In Section 3, energy considerations and properties of spark formation are discussed. In Section 4, the two Picatinny tests and the NOL test are described. The limitations and disadvantages of each test are pointed out; evaluations of the present procedures and suggested improvements are given. In Section 5, a proposed research program in electrostatic sensitivity is described.

REVIEW OF ELECTROSTATIC SENSITIVITY TESTING

Earlier designs of electrostatic initiation tests include those at the Bureau of Mines (Ref 8, 9), NOL (Ref 10), Picatinny Arsenal (Ref 11), Iowa (Ref 12), and the Explosives Research and Development Establishment (ERDE) (Ref 1 - 6). In this section, we shall review the work at ERDE in some detail since it was the most systematic study of spark initiation. The other tests will then be compared with that work. For the purposes of this review, it is important to begin by distinguishing between two types of discharge: arcs and sparks.

Definition and Properties of Arcs and Sparks

Loeb (Ref 13) defines a spark as an "unstable and discontinuous occurrence marking the transition from one more or less stable condition of current between electrodes in a gas to another one ... It may also occur that the transition process may start but fall short of achieving the transition owing to circuit conditions such as power supply (restrictions)."

This definition emphasizes the transitory nature of a spark, but it is too broad for our purposes. Therefore we will define a spark to be a dielectric breakdown of a gas between two electrodes in which the liberation of secondary electrons from one of the electrodes is the major feedback mechanism necessary to sustain the discharge. The liberation of the secondary electron is usually due to both the impact of ions formed in the discharge region upon the cathode and to photoelectronic ionization from the cathode (negative electrode). Photons are produced throughout the gap by the discharge. Spark breakdown is governed by Paschen's law (Ref 13); there is a minimum voltage below which a spark will not pass between two electrodes in a given medium. In air, this voltage is about 275 volts. The spark may be preceded by corona discharge or glow discharge. Essentially, a spark begins by an ionizing event between electrodes and acceleration of the resulting electrons and ions by the applied field. These primary ions and electrons may, in turn, produce additional ionizing events; but breakdown (a high current at reduced voltage) does not occur unless the positive ions and/or photons impinging upon the cathod liberate additional electrons into the gap. A spark is not stable because the cathode will heat up to a point where thermionic emission becomes the important mechanism for the liberation of electrons. The spark is then said to form an arc. Of course, the source of energy (a charge capacitor, for example) may not be able to supply enough energy to complete the transition. An arc thus may be said to be a stable discharge between two electrodes in which thermionic emission is the feedback mechanism responsible for sustaining the discharge.

An arc is commonly formed in two ways: (1) as a result of a spark formation evolving into an arc, and (2) as the result of an initial contact and subsequent separation of two electrodes carrying current. In the latter case, the arc is initially formed by intense Joule heating of the touching electrodes at the point of contact.

Upon separation, the hot cathode emits sufficient electrons to maintain the discharge. An arc is usually accompanied by ejection of hot metal and emission of relatively high frequency radiation (into the ultraviolet). An arc may be formed even at very low voltages.

It may be difficult in practice to distinguish betweer the two types of discharge, since the spark may form an arc if sufficient energy is available. However, if the initial voltage between electrodes in air at atmospheric pressure is less than about 275 volts, the discharge is almost certainly an arc. Often one speaks of sparks as "gaseous discharges", since contact between electrodes is not required, and since many discharges are in fact sparks according to our definition. Similarly, one often speaks of arcs as "contact discharges" or "metal - metal discharges". We will use this terminology in the following discussions, cognizant of the fact that gaseous discharge (a discharge that does not involve contact between the electrodes) may be an arc discharge.

The ERDE Tests

MSW (Ref 11) were the first to recognize the distinction between the contact and gaseous discharges in igniting explosives. The ignition of powdered lead azide as a result of these two mechanisms is shown in Figure 1 (taken from Reference 6). The behavior of the various factors, as shown in Figure 1, can only be observed when the apparatus is arranged so that actual contact can occur between electrodes. It should be noted that all the standard tests at Picatinny and NOL are designed to study the gaseous discharge region only. According to MSW, the peak in the initiation probability at low energies occurs when the voltage across the storage capacitor is about 300 volts and is nearly independent of capacitance. The peak thus occurs when spark formation is barely possible. Ignition at lower voltages must therefore be due to contact discharge. The decrease in probability of ignition above the low energy peak is due to energy loss from the arc to spark formation. Ignition in the high energy range is evidently due to spark discharge alone. Lead styphnate does not exhibit as large a difference in energy between the contact and gaseous discharge regions.

MSW investigated the effects of a wide range of parameters. Two techniques were used: a capacitor discharge between electrodes with a fixed gap, and a capacitor discharge between moving or approaching

electrodes. In the latter technique, actual contact between electrodes permitted arc discharge to occur. The moving electrode technique had the advantage of mechanical simplicity in that no gap needs to be set (see, however, Section 4 for details on one of the Picatinny tests which uses a moving electrode). The disadvantages were that the electrode spacing for spark initiation was necessarily ambiguous due to spark delay and to corona losses. It is generally assumed that a spark discharge will occur between approaching electrodes when the gap voltage equals the breakdown voltage. However, there may be a delay in discharge of the order of microseconds to milliseconds. This delay is statistical in nature and depends upon voltage, electrodes, illumination, and ambient gas (Ref 13). For an approaching electrode moving at 140 cm/second and a spark delay of about 10^{-4} second, the uncertainty in gap width is approximately 0.014 cm or about 0.006 inch. An example of spark delay is shown in the photograph given in Figure 2. In this case, breakdown occurred about one microsecond after the voltage was applied to the gap. The oscilloscope photographs included in this report were taken by the authors using apparatus similar to that described by Gentner ?

The corona losses may be as large as 10% of the energy stored in the capacitor (Ref 13). If electrode movement is very slow, powder may be attracted to the electrode, thus altering the explosive-electrode geometry. On the other hand, the fixed electrode configuration allows one to set an accurate gap and eliminates corona losses; however a fast low-loss switch is required to transfer energy from the storage capacitor to the gap.

For convenience, some of the results of the tests by MSW are summarized below.

Fixed Gap Versus Moving Electrode

In the gaseous discharge region, the curves of initiation probability vs discharge energy were very nearly identical. The moving electrode was used exclusively for the contact discharges, although there was no apparent advantage over a fixed electrode placed lightly in contact with the base electrode.

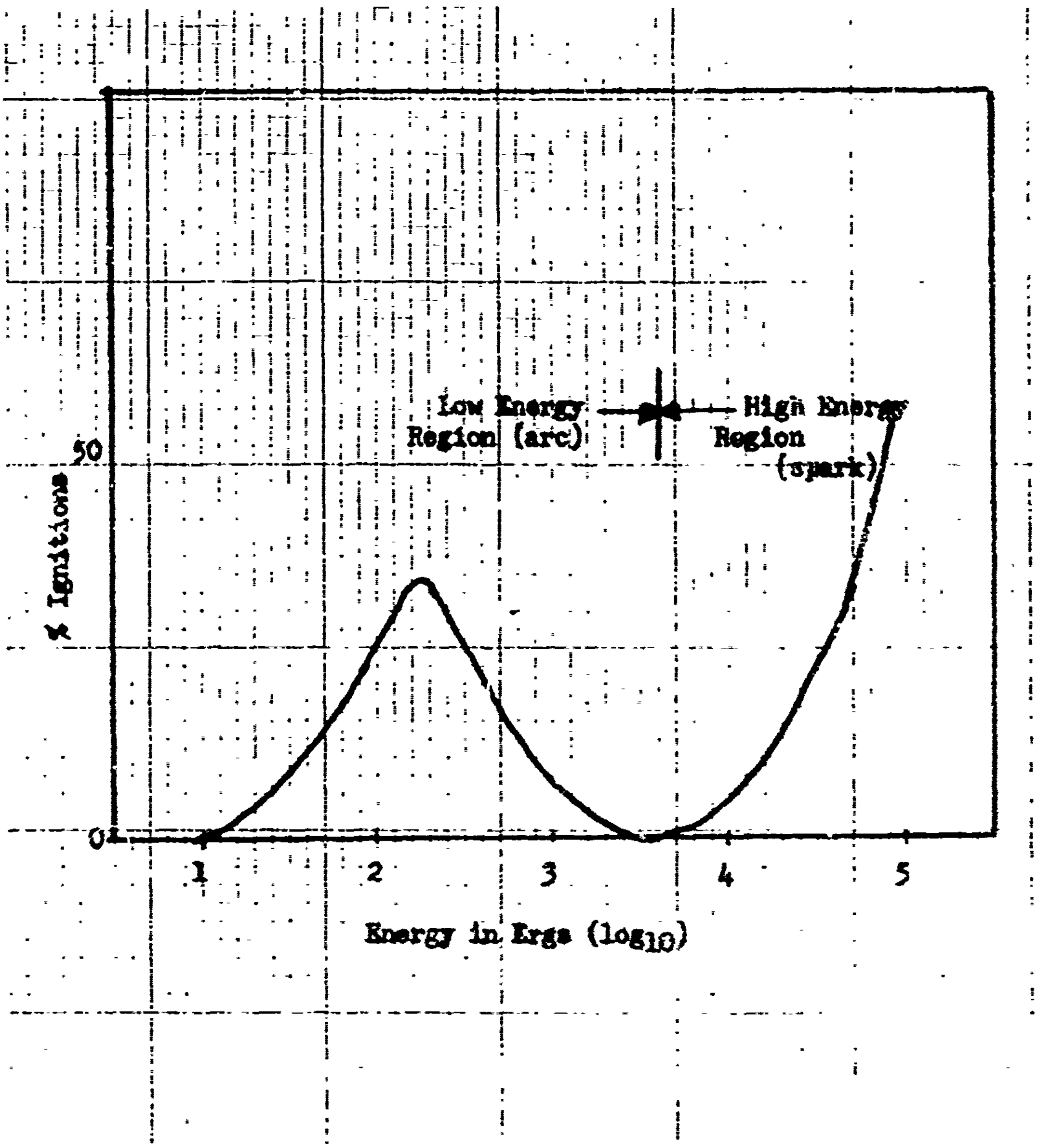
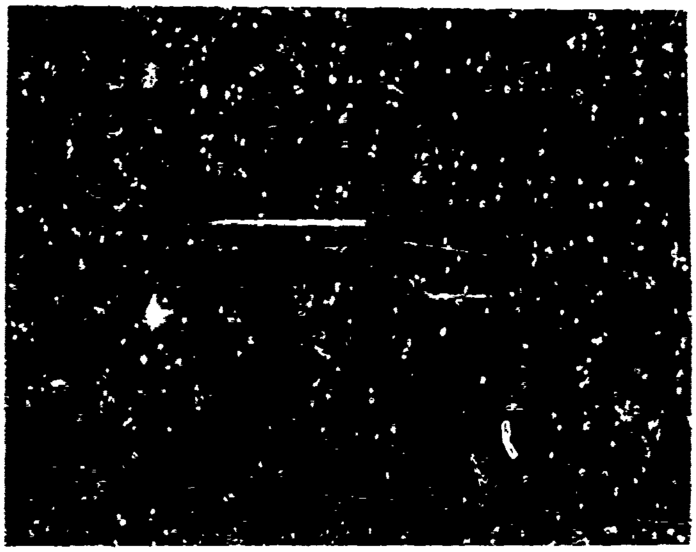


Fig 1 Dependance of ignition probability on energy for lead azide
(C = 1000 pf)



200 V/cm

200 nsec/cm

Fig 2 Voltage across a spark gap

Note: The voltage was applied at t = 0; the discharge began approximately 1 microsecond later (the time scale is 200 nseconds/cm). Note the oscillations and the sustaining voltage remaining on the capacitor at the end of the discharge, a characteristic of a gaseous discharge.

Effects of Electrode Shape

In all experiments, one electrode was a flat plate, the other one approximately needle-shaped (Fig 3). Generally, the probability for ignition was higher for the plumb-bob than for the sharp needle or ball electrode. Differences were less than a factor of two in initiation probability in nearly all cases. The plumb-bob electrode was more easily reconditioned after several trials, but it was more expensive than the needle electrode. Usually, the latter was a steel phonograph needle. The taper of the plumb-bob (and probably also of the needle) did not affect the results. The differences between the two were attributed to the slight additional confinement provided by the plumb-bob. A study also was made of electrode materials, but no important differences were observed among a variety of metals. Loeb (Ref 13) discusses electrode material effects and also concludes that the material is unimportant compared with other variables. When the metal base electrode was replaced by a conducting rubber sheet, larger changes in ignition probability occurred. These changes are discussed below.

Effect of Humidity

Extensive data were not taken by MSW on the effects of humidity. Instead, they chose to control the relative humidity at approximately 40% for all the tests. Since lead azide is not hygroscopic, no effects due to changes in surface conductivity would be anticipated for humidities below about 70% [1]. Loeb (Ref 13), however, points out that impurities in the ambient gas can strongly affect the nature of the spark; hence humidity can play an important role on that account (see Section 3).

Effect of Gap Length

In the gaseous discharge region, the ignition probabilities as a function of energy were largest for gaps of the order of 0.003 - 0.006 in. The probability functions decreased by factors of two to

[1] In unpublished work the authors have shown that the surface conductivity of lead azide is very nearly constant below about 70% relative humidity

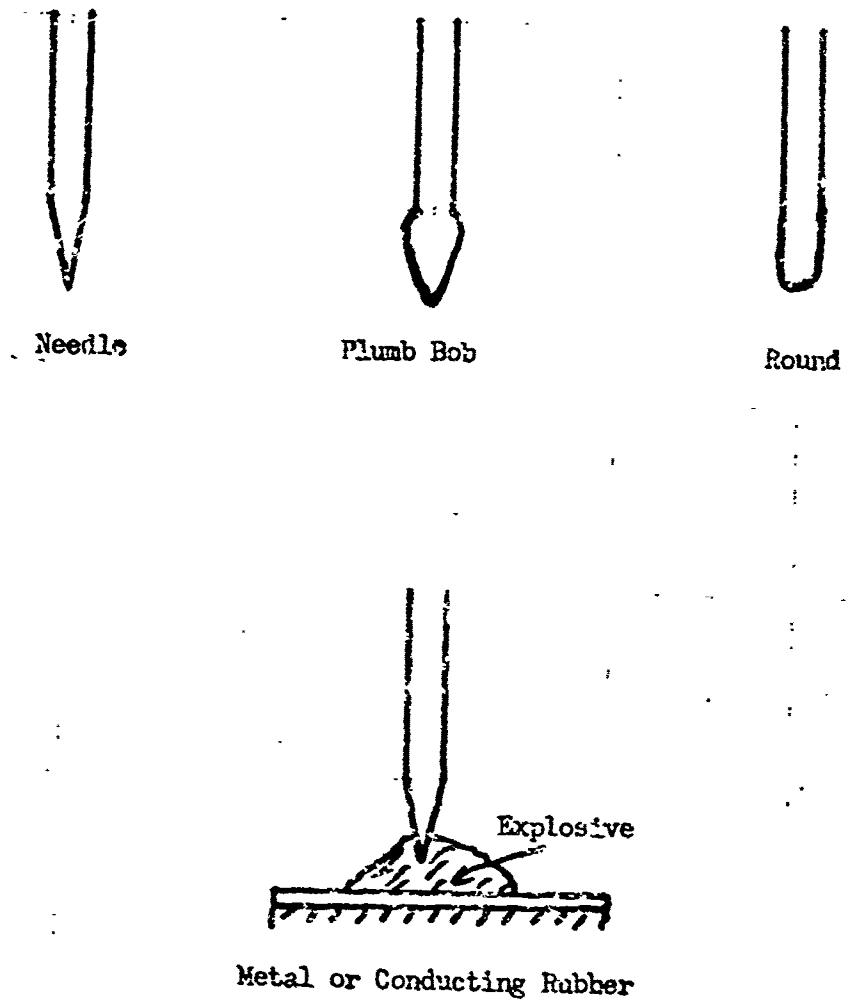


Fig 3 Electrode shapes and sample geometry

three for much wider gaps, i.e., in the range 0.020 - 0.040 in. The results for the smaller gaps imply that one electrode penetrated the explosive; penetration was possible for both the needle and plumb-bob electrodes. The dependence of the ignition probability on gap length is important since the standard tests use fairly wide gaps, i.e., as large as 0.050 in.

Effects of Size of Storage Capacitance

For both the low energy and high energy regions in Figure 1 the probabilities for ignition were very similar for a wide range of capacitance (100 - 1000 pf) when no series resistance was used. The minimum energies for both contact and spark initiation were nearly identical. When a high series resistance was also present, a minimum capacitance effect was observed. That is, regardless of the stored energy, no ignitions were observed for capacitances below a certain value (Ref 6). The minimum capacitance effect was attributed to a splitting of the spark, or a breakup into successive, smaller sparks.

Effect of the Series Resistance

Series resistance was inserted in two ways: as a lumped element in the circuit, and as a conducting rubber electrode with or without additional resistance. The rubber electrode was supposed to simulate, in the laboratory, the resistance of a human. The lumped series resistance primarily affects the form of the discharge, i.e., changes an oscillatory current to a unidirectional one (Section 3). In the gaseous discharge region, the lumped series resistance generally decreased the probability for ignition. For very high resistances - greater than 10^5 ohms - the probability began to increase. Resistances of the order of 100 ohms were sufficient to insure that the current would be unidirectional. In the case of contact discharge, the probability for ignition for lead azide increased for a series resistance of 10^5 ohms. The authors suggested that the slower delivery of energy accounted for the improvement. The minimum energy also was lowered slightly; 12 to 18 ergs vs 20 ergs for no series resistance. The rubber electrode also lowered the minimum energies for gaseous discharge (contact discharge was precluded). the reason for this lowering was not clear. It is true that the duration of the discharge was lengthened; however, the lumped element resistance also lengthened the duration without a concomitant decrease in minimum energy. Evidently the decrease was due to an electrode effect.

Particle Size Effects

Generally, explosives consisting of the smaller particle sizes were more sensitive. Colloidal lead azide was the most sensitive of all the explosives measured by MSW; a minimum energy less than 2 ergs was observed; the reason for this dependence is not known. The effects of particle size distribution and shape were not investigated; it was conjectured that they might affect the probability that sufficient powder would be located between the electrodes, and effect that would be of importance for the narrower gaps and (nearly) touching electrodes.

Other Work

A minimum energy of 10^{-2} erg for ignition of lead azide has been reported by Hanna and Polson using an electrified vibrating probe (Ref 12). They also described a more conventional test; however, a quantitative analysis of the energy delivery is not possible based on their report. Crane, Smith and Bullfinch (Ref 14) performed a statistical analysis to investigate a number of parameters in the ignition of magnesium. Some of the conclusions are difficult to relate to electrostatic ignition of primary explosives since magnesium has a high conductivity; but one important point was made concerning the effects of humidity. One would not expect that humidity would have any effect on the conductivity of magnesium, and thus we must conclude that humidity must affect the nature of the spark rather than the explosive. Another point made by the authors was that it may be dangerous to extrapolate to probability for ignition curves to low energies, i.e., the tails of the distribution should actually be measured. This latter point has important implications in the determination of minimum energy, or for the estimation of acceptable energy levels in hazards analyses.

Gentner (Ref 7) studied the spark initiation of Composition B and lead azide. His work is particularly important because it treated the partition of energy among the elements of the circuit and gap in a quantitative manner. He showed that only about 10% of the energy stored in the discharge capacitor actually was delivered to the spark gap when a series resistance was put in the circuit. Litchfield (Ref 15) studied the spark initiation of organic vapors and emphazized the effects of gap length and "quenching of the spark" by the electrodes, i.e., the electrodes conducting a large amount of heat from the discharge.

ENERGY CONSIDERATIONS AND SPARK CHARACTERISTICS

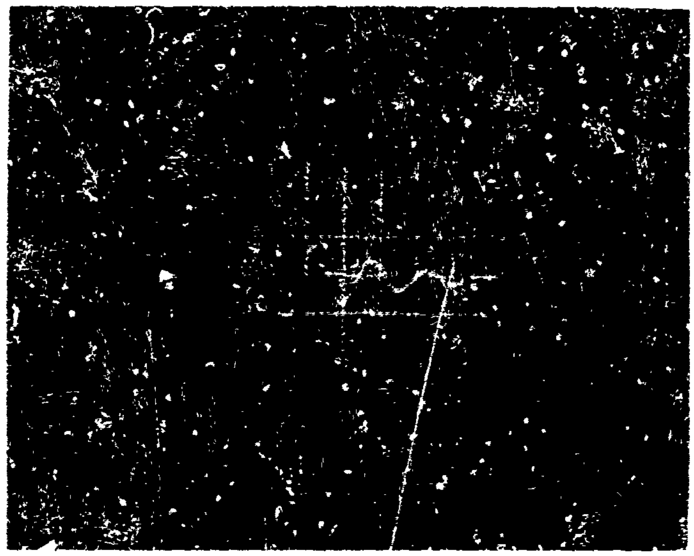
Many of the effects described in Section 2 play important roles in spark initiation because they affect the amount and rate of energy transfer from the storage capacitor to the spark gap. The energy delivery can be determined in part by observations made on the electrical circuit. MSW (Ref 1) carried out these measurements for a limited number of tests and provided some analytical treatment of their circuits. The only quantitative result which can be drawn from their work is that only about 15% of the stored energy was actually delivered to the spark gap when a series resistance greater than 1000 ohms was placed in the circuit. A more quantitative analysis was made by Gentner (Ref 7). From photographs of the current and voltage waveforms, he obtained the same figure (10%) when a small resistor was placed in the circuit. In both of these cases, the current was unidirectional. The remainder of the energy must be dissipated elsewhere. In this section, we briefly discuss these energy losses and examine the roles of the circuit parameters in energy partition in the circuit, and in spark formation.

When no additional resistance is placed in the circuit, the current is controlled by the resistance of the spark gap, the resistance of any switch in the circuit, the stray inductance, the capacitance, and the applied voltage. An oscillating current or "ringing" is commonly observed under these circumstances (Fig 4). If the leads are several centimeters long, considerable energy may be radiated. To illustrate this effect, we will analyze the circuit of Gentner (Ref 7). We assume, for simplicity, that the circuit is a short dipole. The energy radiated is then given by Reference 16:

$$E = \int_{o}^{o} \frac{I_o(t)\,(kd)^2}{12c}\,dt \qquad (1)$$

where k is the wave vector of the radiation, I_o is the magnitude of the current, d is the length of the dipole, and c is the velocity of light. The current $I_o(t)$ depends upon the discharge circuit. In Gentner's work, currents of the order of 300 amperes, frequencies of the order of 10 MHz, and oscillations up to 1 microsecond duration were observed. Choosing d = 10 cm (the length of the radiating wires in the circuit) and substituting into the equation 1, we obtain $E = 10^4$ ergs.

200 nsec/cm



Contact discharge touching

Fig 4 Oscillatory voltage across a contact

Note: Note the absence of any residual voltage at the end of the discharge, in contrast to the discharge of the gaseous type.

This represents 3% of the energy stored in the capacitor. Conservatively, we estimate that up to 10% of the stored energy may be radiated when no series resistance is in the circuit. The radiation would be greatest for the contact discharge case, since in that case the currents are generally larger (refer to Equation 1).

When the energy delivery to the spark gap drops below the energy loss rate to the surroundings and to the electrodes, the discharge stops. For unidirectional current flow case, this point is reached when the voltage drops below the sustaining voltage. This behavior is illustrated by the static current - voltage characteristic of the spark gap, given in the sketches of Figure 5, and the load line of the external circuit. Curves A - C represent the current - voltage characteristic of the spark gap prior to breakdown (pre-breakdown region); curve D - F represents the current-voltage characteristic after breakdown (post-breakdown region). The voltage V_{th} is the threshold voltage for breakdown, and I_{min} is the minimum current after breakdown at which the breakdown can be maintained. These values depend upon electrode shape and materials, the gaseous medium, the separation of the electrodes and, to a lesser degree, the external circuit parameters. The load lines are obtained in the following manner: A line with the slope $-1/R$, where R is the value of the series resistance, is drawn intersecting the abscissa at the voltage across the storage capacitor. Thus the line through the points C and E shows that there are two possible states for the spark gap. During a discharge, the following processes occur: The voltage across the spark gap increases to the threshold voltage (point C). At this point the voltage across the capacitance is V_i. A transition occurs (breakdown), and the operating point changes to point E. The capacitor discharges through the spark gap with a concomitant decrease in voltage across the capacitor and gap. When the voltage across the capacitor reaches V_f, a further decrease in voltage requires a decrease in current below I_{min}. The discharge therefore ceases, and the operating point switches to point B. The voltage left on the capacitor is thus V_f. The value of V_f depends upon the value of the series resistance as can be seen by comparing the curves in sketches a and b of Figure 5. It is evident that a higher series resistance will cause cessation at a higher value of V_f.

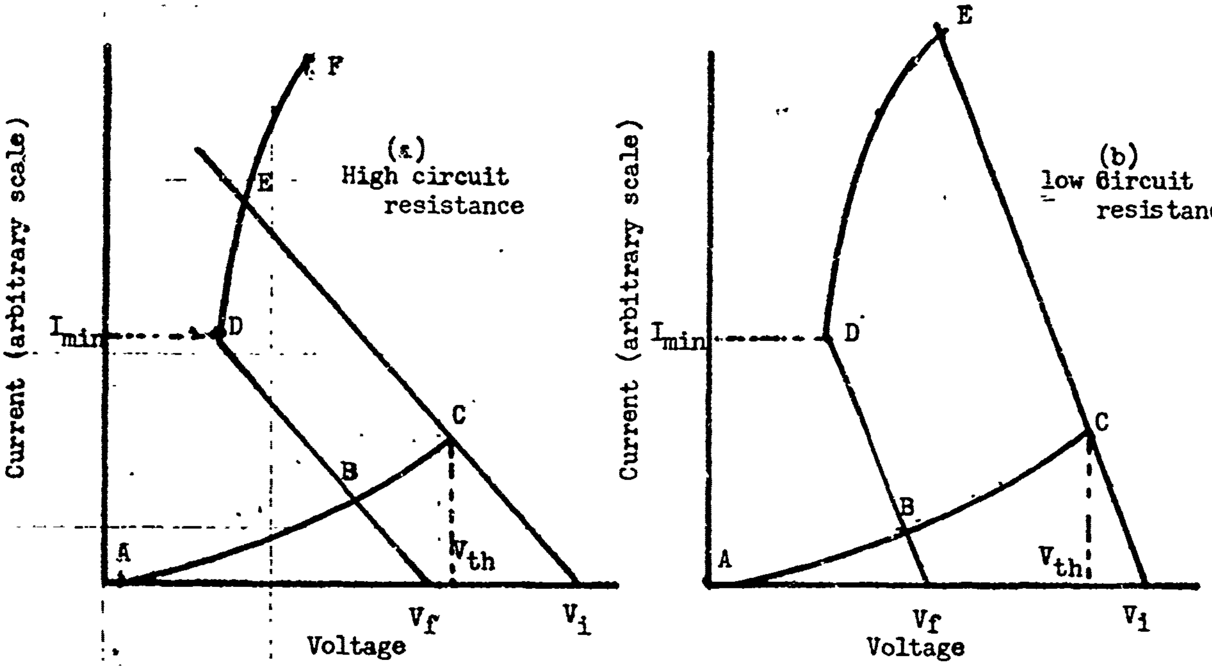
The same behavior for an oscillating discharge cannot be illustrated on the static discharge curves. In this case, the discharge is best described in terms of energy alone. However, the discharge ceases in much the same manner as is shown in Figure 5c. An oscillating discharge is noted until the voltage decays below a certain point at which the voltage across the spark gap remains constant. It also should be noted that the cessation voltage can have either sign at the time discharge stops. The cessation voltages for spark gaps is of the order of 200 volts. The fraction of stored energy remaining on the capacitor may vary over wide limits depending on the initial voltage on the discharge capacitor:

$$\text{Fraction of energy remaining} = V_f^2/V_i^2 \qquad (2)$$

where V_f is the cessation voltage and V_i is the initial voltage on the capacitor.

In the case of contact discharge, the cessation voltage is nearly zero as illustrated in Figure 4. One way to distinguish the two types of discharge is to observe the current or voltage decay and to determine whether a cessation voltage occurs.

A fraction of the stored energy must be used to initiate the spark. This energy includes that needed to heat the electrodes. For gaps smaller than 0.003 in., the electrodes can serve as effective heat sinks for the spark discharge since a large fraction of the spark energy is dissipated in the vicinity of the electrodes. Litchfield (Ref 15) defined an ignition quenching distance which represents the smallest separation of the electrodes at which the apparatus does not extract significant heat from the developing spark kernel. This quenching distance obviously depends upon the shape and the thermal conductivity of the electrode. Engergy loss to the electrodes can be minimized by using larger gaps; however, the spark energy may then not be effectively delivered to the explosive. MSW (Ref 2) also present a qualitative model for length. Electrode losses are, of course, particularly severe for contact discharge. The low minimum energies reported by MSW (Ref 6) for the rubber base electrode may be due to the low conduction of heat from the discharge by the base electrode.



(c) **Oscillatory Discharge,**

showing + cessation voltage

Fig 5 Current-voltage characteristic of a spark

The series resistance has a number of effects on spark formation and energy delivery. A sufficiently high resistance can reduce the discharge current to the point where spark splitting or incomplete spark formation occurs. This effect is illustrated in Figure 6, which shows the static characteristics of the spark gap; the indicated points are the same as those in Figure 5. In this example, the series resistance is assumed to be so large that it does not connect stable operating points in the pre-breakdown region. This can occur if the minimum current for maintenance of the breakdown is larger than the current at the threshold for breakdown, a very common situation. Thus in this example the trajectory of the current is limited to the unstable region between the pre-breakdown and post-breakdown regions. Several small spark kernels may develop and decay without reaching the threshold energy needed to ignite the explosive. A related effect may be understood by referring to the equivalent circuit of Figure 7. When the breakdown first occurs, the capacitance of the electrodes is discharged through the spark resistance. If the series resistance is small, the spark electrodes recharge almost immediately to the sustaining voltage. A large series resistance limits the recharging rate; in this case the time for recharging is governed by the capacitance of the electrodes rather than the storage capacitor. Characteristic spikes then appear in the voltage across the gap, as shown in Figure 8. In the test used to obtain Figure 8, an 82 ohm resistance was in series with the gap. The gap capacitance was approximately 200 pf and yielded a time constant of 16 nsec. The spikes in Figure 8 thus might be a result of this spark discharge and recharge. The relatively smoother current flow is a result of the parasitic inductance in the circuit.

The storage capacitance value also affects several properties of the discharge. There is, of course, the indirect effect, i.e., the requirement for higher voltages to obtain a given stored energy, $E = 1/2CV^2$. Thus a smaller capacitance results in less sustaining voltage energy left in the capacitor after discharge. The capacitance also affects the rate and the nature of the discharge, i.e., unidirectional vs oscillatory. When the series resistance is small, the rate of energy delivery may be faster than the rate at which the temperature of the explosive rises. Thus MSW (Ref 2) observed that the value of the capacitance did not strongly affect the probability for ignition due to sparks. However, when a larger series resistance is present, either lumped or in the form of a rubber electrode, the results are not so easy to interpret. A minimum capacitance was necessary to

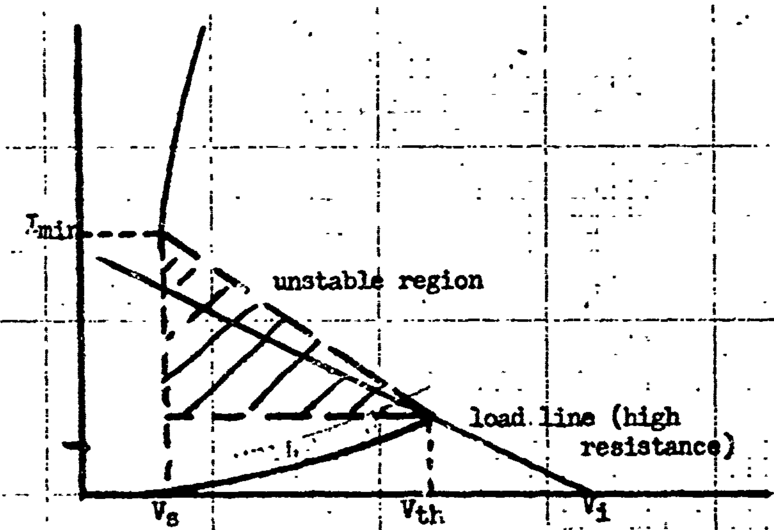
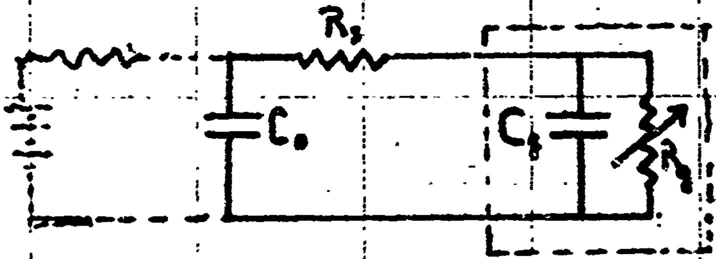


Fig 6 Static characteristic of a spark: Unstable spark



R_s - series resistance

C_o - storage capacitance

C_g - interelectrode capacitance of gap

R_g - gap resistance, a non-linear quantity

Fig 7 Equivalent circuit of spark discharge apparatus

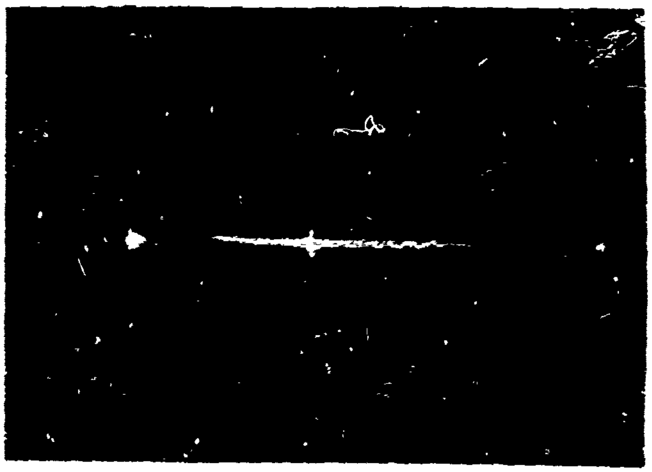


Fig 8 Spark discharge showing spikes

avoid spark splitting. Wyatt (Ref 17) in work done at NOL, also observed an interesting capacitance effect illustrated in Figure 9. Here the minimum energy at a given storage capacitance is that which did not ignite the explosive once in fifty trials. The significant point is that the minimum energy curves for lead azide and for lead styphnate cross. Thus a relative sensitivity test apparatus could invert the order of the explosives or rank them as equally sensitive. The manner in which the capacitance and resistance affect the spark formation and behavior remains an important question. Certain factors are qualitatively understood, e.g., the effect on energy delivery rate and load line effects; however, the dynamics of spark formation, spark splitting, and minimum capacitance effects are thus far poorly understood.

Humidity can affect spark breakdown by a measurable amount. Shown in Figure 10 is the breakdown voltage across a gap as a function of relative humitidy (Ref 16). The twenty percent variation leads one to assume that the role of humidity on spark initiation of explosives may not be merely an effect on the explosive alone.

PRESENT TESTING PROCEDURES

Picatinny Test No. 1

The apparatus is described by Kirk, Perkins, and Clear (Ref 11). Briefly, it consists of a motor-driven probe which moves to a set gap, remains stationary for a specified time, and then moves back to the starting point. The capacitance can be varied from 10^{-4} to 0.1 microfarad, and the voltage may be varied from 1.0 to 5.0 kv. No humidity control is present. The schematic circuit is shown in Figure 11.

This test is used to characterize explosives submitted by various directorates of the Arsenal. It appears, however, that the users do not completely trust the test to yield relative sensitivity, since widely varying results are obtained, depending on the humidity, the operator, and the test setting.

Specific difficulties with the test include:

a. The setting of the gap is accomplished with a feeler gauge rather than with a direct-reading instrument such as a dial indicator.

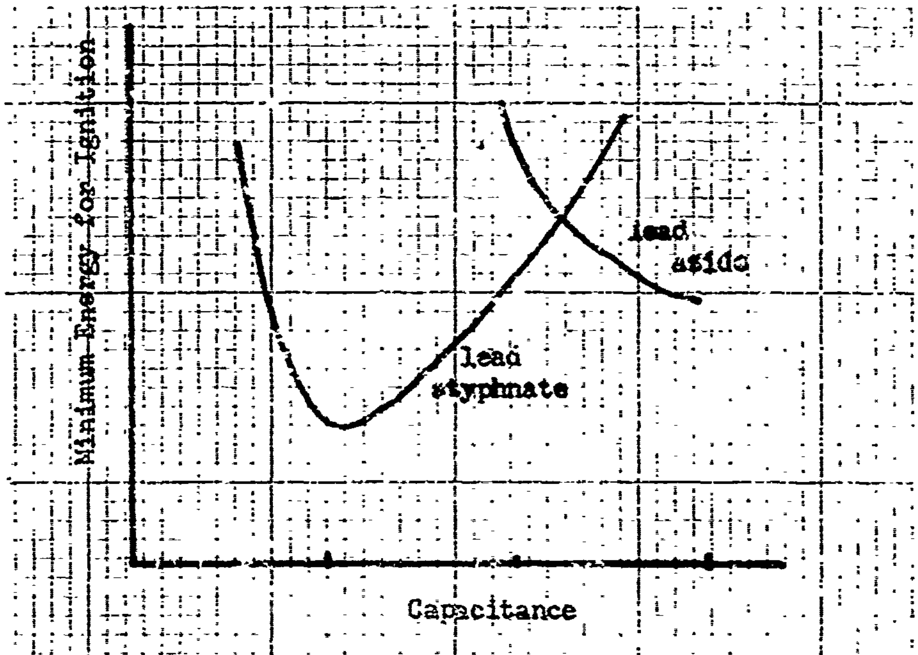


Fig 9 Dependance of ignition energy on capacitance (arbitrary scales)

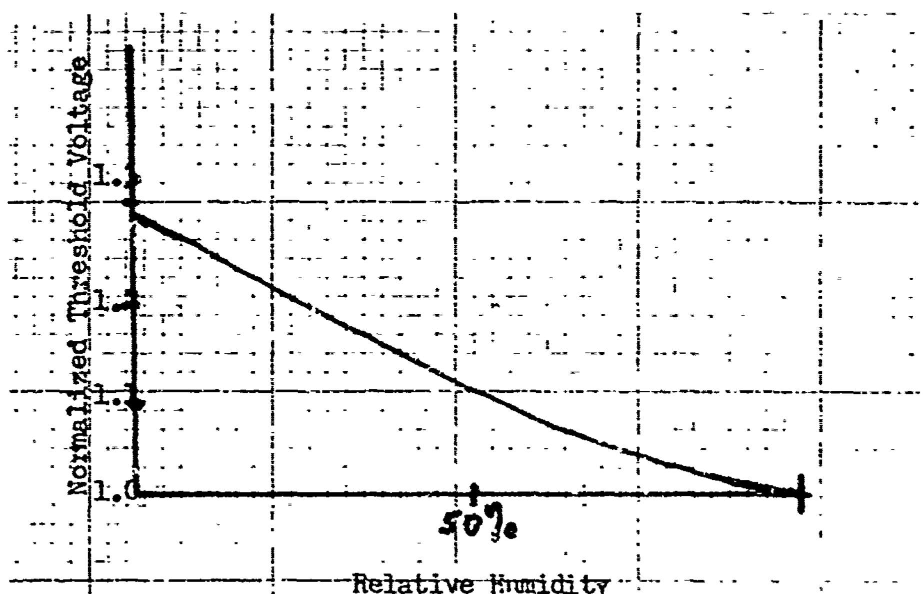
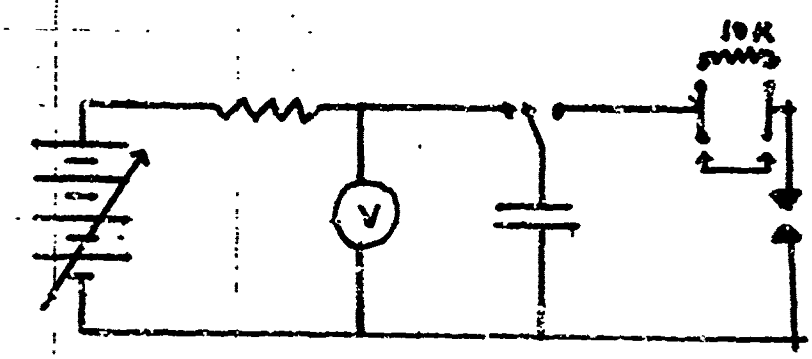
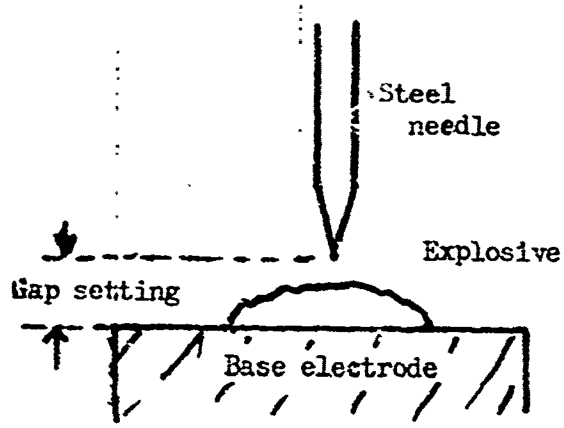


Fig 10 Effect of relative humidity on spark voltage



a. Test Circuit



b. Electrode configuration

Fig 11 Picatinny Test No. 1

b. The determination of whether an ignition occurred depends upon the judgment of the operator; i.e., some report only complete detonations, others include also any sign of decomposition.

c. There is no humidity control, as mentioned above.

d. There has been no characterization of the discharge and electrical circuit.

e. Large variations in probabilities for ignition with changes in capacitance at constant energy were observed by users. This makes the initial choice of settings important in determining relative sensitivity.

Feeler gauge setting can be inaccurate and time-consuming. The inaccuracy of the gap is alleviated somewhat by the rather slow variation of the ignition probability with gap length (Fig 13 in Ref 2). However, the needle is apparently easily knocked out of alignment on detonation, and if it is not readjusted or periodically checked, erroneous results can be obtained. For example, minimum energies of less than 500 ergs for lead azide were reported by the Applied Chemistry Branch at Picatinny Arsenal. Examination of Figure 1 might lead one to conclude that that particular sample was more sensitive to spark discharge, by a factor of approximately twenty, than that used by MSW, or, more likely, that the needle had touched the base electrode, and contact discharge had occurred.

As mentioned above, the operator must use his judgment to determine whether an ignition has occurred. Sometimes the powder is merely blown by the spark, and more often the spark is difficult to observe, and burned powder is difficult to detect. A relatively small number of samples is used to measure minimum energies; on some occasions there were ten trials with no fires. Hence it is easy to miss the one trial which may emit smoke, or cause only light burning.

The lack of humidity control is regarded by the present users as the most serious problem. The Applied Chemistry Branch uses the test only when the relative humidity is below 20%, thereby restricting use of the apparatus to the fall and winter months. The users report that humidity variations affect their results by more than an order of magnitude.

No measurements have ever been made to characterize the electrical circuit. Relatively long leads are used, hence the parasitic inductance may be large. A series resistance of 10^4 ohms is occasionally used to reduce blowing of the powder by the spark, but its effects on energy delivery are unknown. A systematic study of the spark gap length settings has never been made. A rather arbitrary gap of 0.019 in. is used in most cases, a 0.010 in. gap for some of the less sensitive explosives. Despite the fact that MSW found only small variations of minimum energies with capacitance (no series resistance), relatively large variations are found in the Picatinny test; some of them, for the lower capacitance values, may be due to a large parasitic capacitance. The lowest capacitance value is 100 pf, and stray capacitances of this magnitude are not uncommon.

These variations raise a serious question concerning the testing methodology. In the present procedure, the operator chooses an intermediate capacitance and voltage, and reduces the latter until a minimum energy is obtained. Actually, one should obtain a minimum energy for every given configuration and test setting. Wyatt (Ref 17) obtained a different minimum energy for every capacitance in his measurements, as shown, e.g., in Figure 9.

One is usually interested in the lowest energy that will ignite the explosive, the minimum of the "minimum energies". To illustrate this point, we introduce the concept of the "sensitivity map" shown in Figure 12. This map is a surface of constant probability plotted as a function of several variables. A multidimensional space would be required to represent the surface adequately, but for simplicity we have chosen capacitance and energy and a thrid variable (on the X-axis). This last quantity might represent the energy delivery rate (resistance) or some other measure of energy transport. It is apparent that an arbitrary choice of starting point (o) and a variation of a single parameter such as capacitance would not necessarily lead to the minimum energy. It is also possible to trap oneself in a local minimum. Obviously one needs a better procedure.

The necessary improvements are suggested by the critique given above. At the very least, some of the energy delivery is needed, improvements in the testing methodology should be introduced , and humidity control should be provided.

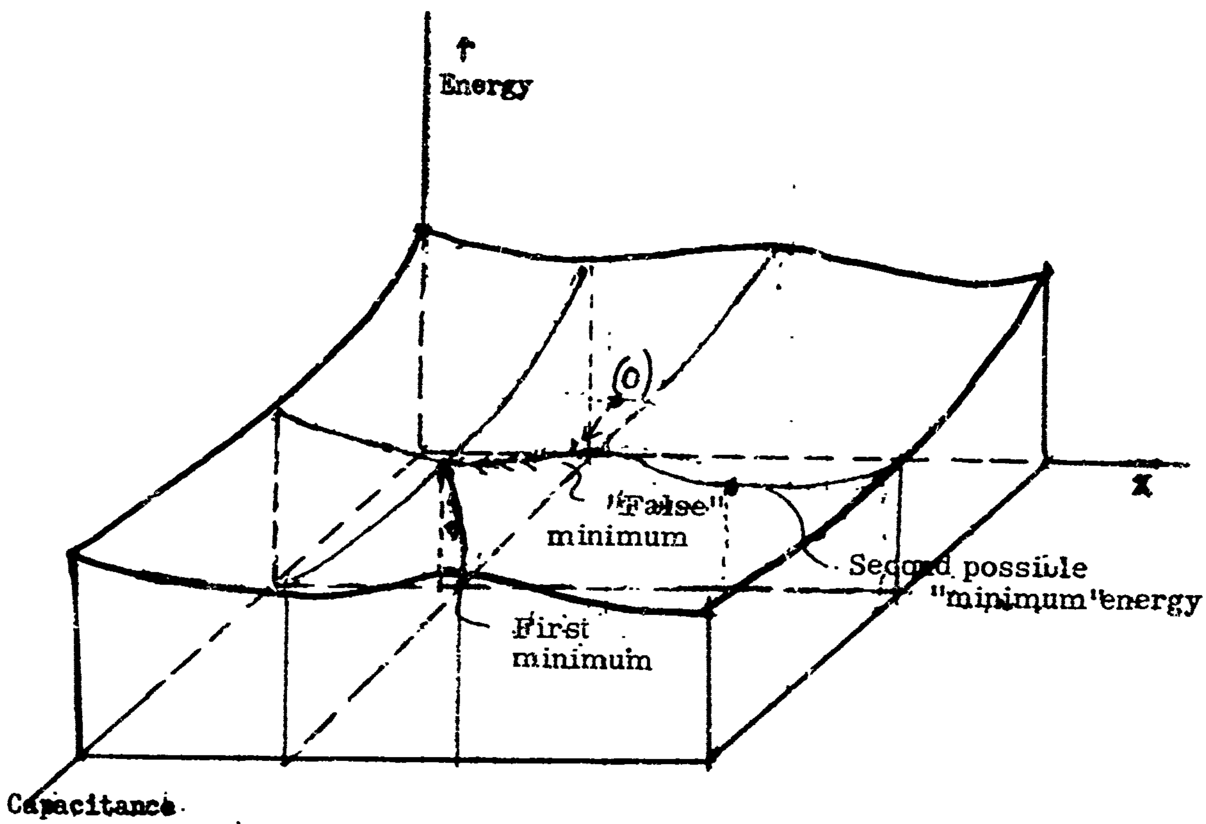


Fig 12 Sensitivity map

Picatinny Test No. 2

A complete description of the test has not been published, although a report of some of the results has (Ref 19). The apparatus consists of a fixed gap electrode which uses steel needles. The discharge circuit is similar to that of the Picatinny Test No. 1. The gap length is set with a feeler gauge, most commonly at 0.005 in.

In nearly every respect, this test is inferior to the first test. Perhaps the greatest problems are associated with possible, or even probable, operator error. An ignition or detonation is considered to occur whenever a spark is observed, i.e., whether or not the explosive is ignited. A safety hazard is always present, since the electrodes are housed in a wooden box that cannot be easily cleaned. The electrical circuit has not been characterized; the losses in the test apparatus are unknown. This test may be useful only for distinguishing primaries from boosters.

Tests at the Naval Ordnance Laboratory

Two apparatuses are used at NOL. The first was constructed by Wyatt (Ref 17) and is very similar to the approaching-electrode apparatus used in the ERDE work. Wyatt showed that sensitivities of explosives used in the United States were similar to those used in Great Britain. This apparatus has apparently not been used for recent tests at NOL, presumably because it is inconvenient and time consuming.

The second apparatus is of more recent vintage and was constructed by Montesi (Ref 10) to provide faster testing operation. This test was intended to provide relative sensitivity only and was designed with simplicity and reproducibility in mind. The efficiency of transfer of energy from the capacitor to spark gap is not considered. A fixed electrode configuration is used for all tests. The electrical circuit uses fast switches and modern circuit techniques. Additional details include:

a. Gap length of 0.050 in.

b. Fixed series resistance of 100 ohms

c. Capacitance of 0.01 microfarad, or occasionally 0.001 microfarad for the more sensitive materials

d. Test voltages of 1,000 to 15,000 volts

With these settings, a minimum energy of 30,000 ergs was obtained for lead azide. This value is more than a factor of four larger than those obtained at ERDE for spark initiation. These settings were obtained by Montesi by varying the setting until the widest separation between the sensitivities for various primary and booster explosives was obtained. The test may be useful only for distinguishing between booster and primary explosives by spark initiation tests. The test procedure is subject to the same criticisms as given for Picatinny Test No. 1; e.g., the test may invert the sensitivities among primary explosives as discussed in Section 2.

In principle, however, the test apparatus constructed by Montesi could be used for a more extensive investigation of minimum energies, since it is well designed and sufficiently flexible to use in a research program.

A PROPOSED RESEARCH PROGRAM FOR ELECTROSTATIC SENSITIVITY TESTING OF PRIMARY EXPLOSIVES

The research work at ERDE provided answers to many questions concerning spark and contact initiation. The minimum energy values obtained by MSW for lead azide and lead styphnate (at humidities of 40%) are likely to be accurate within a factor of two; i.e., even considerable improvements in techniques and apparatus are not likely to yield significantly lower values. Nevertheless significant questions remain. In this section, we outline these questions and propose a program that should provide some answers.

<u>Significant Questions</u>

a. Can a relative sensitivity test and testing methodology be developed that will reflect the sensitivity of explosives in a meaningful manner?

b. How does the energy delivery rate affect the ignition probability? Is there a difference between initiation by oscillatory and unidirectional discharges?

c. Can spark initiation be described in terms of energy density at the surface of the explosive ? Are the effects of the different test settings a matter of efficiency of energy transfer to the surface of the explosives ?

d. How do the sensitivities vary with conditions in the Laboratory and in a production line ? What are the effects of humidity, confinement, etc ?

e. How should the minimum energies be used in a hazards analysis ? How do the minimum energies correlate with chargeability, impact sensitivity, friction sensitivity, time-to-explosion testing ?

f. What new insights into initiation can spark initiation yield ? What role does electrostatic discharge play in impact and friction ?

The differences among primary explosives raises an important question on whether a universal test apparatus and procedure can be developed. Initial test setting may have to be varied too widely to get into the region of the sensitivity map near the absolute energy minimum and to avoid getting trapped in a local minimum. The fundamental similarities and differences in spark and contact initiation among the primary explosives will have to be established.

The energy delivery rate is widely varied in the standard tests without considering its effects on initiation. Perhaps an improved test procedure would involve varying the energy input while holding the delivery rate constant. This might require a simultaneous variation of several elements in the discharge circuit. MSW (Ref 2) speculate that the mechanisms for initiation for oscillatory discharges may be different from those of unidirectional discharges. They suggest that the energy delivery rate should be kept constant, and time to initiation studied to investigate such a possibility.

Clearly, any improved procedure should include a study of actual energy delivered to the spark gap as a function of test settings. A study of the energy density in the vicinity of the explosive is a difficult matter. Even photographs of the spark gap during discharge may not be sufficient although they may be informative.

It has been well established that the sensitivities of primaries vary with a number of conditions. Humidity is one of the more important variables; MSW did not study its effects although they recognized its importance. Confinement is another important variable. In many tests, the spark blows the powder away from the electrodes, thus decreasing the probability of ignition.

The actual energy needed to initiate some of the common explosives is extremely small. Does it make sense to use values as small as the one erg observed by Hanna and Polson (Ref 12) to design a production line for lead azide ? One erg is equivalent to a 100 pf capacitor charged to 45 volts: yet a spark will not form for voltages less than about 275 volts. Is contact discharge a real hazard ? MSW showed that lead azide has a lower minimum energy, but lead styphnate has a greater frequency of accidents. Clearly, minimum energy as such is not the only measure of the hazards associated with a primary explosive; it cannot be separated from the mechanism of energy transfer.

Finally, spark initiation is a process which may involve ignition in the nanosecond time region. In many of the other initiation tests, explosives on a much longer time scale were studied. The time-to-explosion in a spark initiation test may be a more sensitive variable of surface properties, density, particle size and shape, temperature, etc., than certain other tests.

Difficult though all these problems may be, they should be worth investigating, since a well designed spark and contact initiation test may prove to be a valuable complement to the overall study of explosives as well as a hazards test.

Proposed Research Program

We propose to develop a spark and contact initiation test and testing procedure to answer the questions outlined above. The test will include the following provisions:

a. Control of humidity

b. Study of energy delivery rate and partition among the circuit elements. (This requires a flexible circuit design.)

c. An electronic assist to determine whether ignition occurs

d. A degree of automation to speed up testing, in particular to determine the tails of the probability distributio'

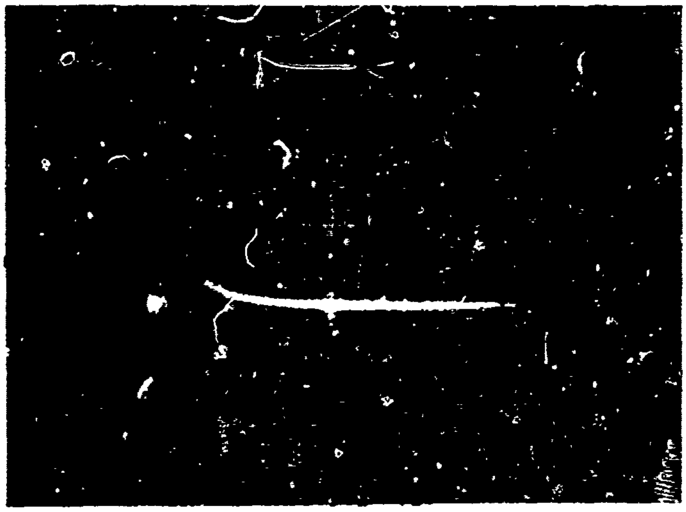
e. Photographic study of spark and contact initiation

The design of the discharge circuit is the simplest of the tasks. Fast, low-loss switches are available. Mercury-wetted contact relays are capable of nanosecond switching speeds and are useful to 1000 volts. For higher voltages, cold cathode, gas filled switch tubes - available commercially - are satisfactory. Dual beam oscilloscopes, such as the Tektronix 555, are available for study of current and voltage transients.

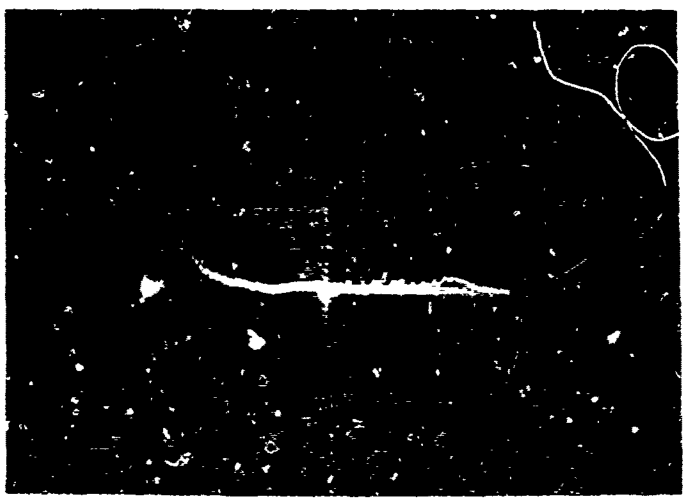
To determine whether an ignition occurs and to determine time-to-explosion, we propose to use a storage oscilloscope such as the Tektronix 434 Split-Screen oscilloscope. Generally, spark discharges are sufficiently reproducible for a deviation from a given pattern to be interpreted as explosive detonation. Figure 13 shows a photograph of a spark discharge when no ignition occurred; below it is a photograph of a discharge when explosion did occur. From these photographs, one can determine the energy delivered to the spark, the time to explosion, and the energy delivery rate versus time. A storage oscilloscope provides a quick way to record and to compare such transients without the delays of film development, exposure, and other camera nuisances.

A high speed image converter camera (TRW) is available to photograph spark formation and discharge. Practical difficulties may include triggering and light levels; however, the values of the information on spark-explosive interaction makes it worthwhile to expend effort to overcome these problems.

Thought has been given to the feasibility of an automated testing procedure. Such a scheme would be worthwhile in reducing costs and time of a large-scale study of sensitivity, in which very large numbers of samples or individual tests would be required. An automated procedure would also make possible the determination of sensitivity curves to lower levels than are now feasible, with a concomitant ability to extrapolate, with improved accuracy, to low probability levels. This is important in the practical problems of



a. Discharge without explosion. (Voltage on left half, current on right half)



b. Discharge with explosion. (Note the dip in the voltage trace and the perturbation in the current trace between 300 and 400 nseconds)

Fig 13 Oscillographic detection of explosion (1800 pf capacitor charged to 1750 volts. Vertical scales, 10 amp and 500 volts/cm. Time of scales, 200 nsec/cm on all traces)

estimating hazards. Some of the features of a proposed scheme involve the use of stepping motors and the digital control of a sample table holding many - say 100 - samples, and the possible design of a cheap, mass-produced sample in which the electrodes are integral with the sample assembly.

The most challenging aspect of the program will be the development of a testing methodology. One possibility would be to use a modified method of steepest descents. In this approach, one would choose an arbitrary starting point (or, more realistically, one based on experience) and incrementally vary the test setting about this point to determine the lowest energy for ignition. That setting would then be the starting point, and the procedure would continue. In this manner, one might attempt to approximate the curve of Figure 11. Another approach might be to examine and extremely large number (several thousand) of explosive samples under a given condition and assume that this large sample would include or represent all of the important explosive-spark gap geometries and degrees of confinement, etc. This is the ensemble average approach. Either approach requires a high degree of automation. Ultimately, we expect to identify reasonable starting points and test settings, including spark gap length, confinement, humidity, storage energy, and delivery rate for each primary explosive.

We propose also to gather enough information on the common primary explosives so that an intelligent estimate of hazards associated with the production and handling of these explosive can be made. This will require, not only a measure of minimum energies, but also a study of the nature of the discharges that are likely to occur in a laboratory or production line. A correlation between spark sensitivity, and the time-to-explosion testing will be attempted.

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